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# ANALYSIS OF LANDSCAPE TRANSFORMATIONS IN THE URBAN-RURAL GRADIENT OF THE METROPOLITAN DISTRICT OF QUITO

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**Abstract:** The relocation of services in the peripheries and the new urban expansion patterns have dramatically altered the periurban landscapes. However, due to its transformation speed, there is limited knowledge regarding the spatiotemporal changes of these interstitial territories. By calculating landscape metrics in high resolution satellite images, this research analyses spatiotemporal transformations in the Metropolitan District of Quito urban-rural gradient, testing a novel and accurate method to identify urbanisation tendencies. The results evidence the main role that new road infrastructures have had in urban expansion. Also, the analyses reveal significant changes in agricultural coverages (related to the subdivision of rural lots) and the processes of vegetation fragmentation, evidencing the environmental fragility of these territories in transformation. Finally, the Markov chains modelling technique was applied, exploring the landscape change probabilities in the following years. This methodology can be particularly useful in land-use planning policies since it provides precise knowledge about the main tendencies of urbanisation.

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# Introduction

During the past century, the urban world's population has rapidly increased, drastically transforming landscapes around the planet. Furthermore, the limits of the entity known as "city" have tended to be diluted, forming territories with urban attributes but expanding in an unlimited and diffuse pattern. According to De Mattos (2016), this metamorphosis of the city happens as a result of financial globalisation, economic restructuring (deindustrialization and neoliberal development) and the information and communication revolution. This has resulted in the relocation of urban services in the peripheries, which are increasingly better connected by new road infrastructure and the increased access to private motorization. Similarly, Borsdorf (2003) associates the dispersed pattern of contemporary cities with the increase of new interurban highways and the relocation of artefacts of globalisation, such as malls, airports, industrial and technological platforms in areas that were previously mainly rural.

This expansion model has particularly promoted the localization of new residential units for elite classes in the peripheries (Smith 2012, UN Habitat 2013). In Latin-America, these units are typically gated communities (Hidalgo et al. 2007, Frediani 2013), and sometimes they adjoin pre-existent informal settlements, showing complex patterns of socioeconomic segregation (Da Cunha and Rodríguez Vignoli 2009, Durán et al. 2016, Ortiz Báez et al. 2020). These new residential units are also characterised for their low building density and monofunctional activities, representing an antagonistic model to the central and compact city (Albarracin 2017, Serrano and Durán 2020). In this sense, the functional fragmentation of the urban structure, the unequal provision of services, and the lack of connectivity complicates the spatial mismatch between the residents of peripheral areas and their places of employment. Their need to commute to workplaces generates a saturation of road infrastructures, increasing the levels of vehicular pollution and travel times (Ávila Sánchez 2001, Cruz-Muñoz 2021).

Furthermore, the expansion of human activities over rural and natural territories alters the landscape structure, affecting this socio-ecological system (Gallopín 2003). From an ecological perspective, the landscape composition and configuration determine the capacity to provide, manage and sustain the quality of resources indispensable for human life (Lee et al. 2015, Vizzari and Sigura 2015, Inkoom et al. 2018). One of the most severe impacts in landscape structure has been fragmentation, either due to the land covers' subdivision, the conversion from native to designed covers or the development in a non-contiguous pattern. As Shrestha et al. (2012) state, fragmentation can significantly alter ecological functions and processes, reducing habitat and wildlife corridors, decreasing agricultural and forest productivity and, finally, affecting ecosystem services.

In this sense, quantifying the landscape structures facilitates a better understanding of the urban-rural conditions of a territory, the land use patterns, and the transformation of land use through time. The quantification of the landscape structure is also useful for evaluating the ability of the landscape to perform ecological functions and processes, and for monitoring the provision of ecosystem services (Inkoom et al. 2018). Landscape metrics have been widely used for measuring the landscape composition and configuration and for evaluating landscape mosaics (Antrop and Van Eetvelde 2000, Solon 2009, Buyantuyev et al. 2010, Liu and Weng 2013, Fan and Myint 2014, Lee et al. 2015). Although landscape metrics were originally developed from an ecological perspective, they are more and more frequently used in studies with broader approaches (Xing and Meng 2020) and they have shown to be useful for sustainable strategies in territorial planning (Weng 2007, Lee et al. 2015, Vizzari and Sigura 2015). Finally, since landscape change is a dynamic process and the direction and magnitude can vary depending on each environment, analysing the urban-rural gradient has shown to be a useful tool to capture the spatiotemporal complexity of urban dynamics (Yu and Ng 2007, Shrestha et al. 2012, Wadduwage et al. 2017).

Several authors have developed theories in order to understand and characterise the complexity of these interstitial territories. Concepts such as "exopolis" (Soja 2008), "fragmented city" (Borsdorf 2003) or "postborder city" (Dear and Leclerc 2003) have been explored, presenting valuable but generalised approximations. Although the limitless expansion of contemporary cities is a common phenomenon, the specific spatial patterns of this development and its rhythm of transformation may vary between regions, countries, and their particular environments.

In this article, the transformation of the spatial patterns in the Metropolitan District of Quito (MDQ) is analysed. This metropolitan area has shown the fastest urban population growth in the Ecuadorian context in the last years, and the city of Quito (the urban area of MDQ) spatially tends to follow a dispersed and fragmented pattern (Municipality of the Metropolitan District of Quito 2011, Serrano and Durán 2020). However, there is a lack of research regarding the patterns and spatiotemporal transformation along the urban-rural gradients of the city. The goal of this research is to quantify the last decade of transformation for the MDQ urban-rural landscape patterns, and to forecast the probabilities of future tendencies of land cover changes.

Our hypothesis is that, due to its current pattern of expansion, natural and agricultural covers are being particularly affected by fragmentation processes. However, these impacts have dissimilar levels of intensity depending on the infrastructure and other urban services implemented (differently) in various sectors of the MDQ periurban area. In this sense, we also present a discussion about the main drivers of these spatiotemporal changes and formulate some recommendations focused on territorial planning.

# Methodology

## Study area

The MDQ is located in the Andes region, and it is administratively organised into 65 parishes, 32 being urban and 33 rural (Figure 1). This metropolitan area encompasses the city of Quito, the Ecuadorian political-administrative capital. The MDQ economic dynamism and its national and international connectivity constitutes an important attractor node of people and activities. In the last decade, its population has increased from 2 239 191 people in 2010 to 3 059 097 people in 2020, according to the Municipality of Quito (2016), and it is currently the most populous city in Ecuador. Due to its marked altitudinal variation (500 m to 4780 m above the sea level) and its complex topography, the MDQ has more than 15 types of ecosystems, presenting a great biodiversity along its climatic floors, rivers and streams (Municipality of Quito 2016).

From the Spanish foundation of Quito in 1532 until the end of the decade of 1990, the city grew following a clear north-south longitudinal axis, which topographically corresponds to the plateau located between the Pichincha volcano and the eastern valleys of the district. However, in recent years, the urban limits have overgrown (Figure 2), moving towards the eastern valleys, which are experiencing an accelerated transformation in relation to the gradual growth of the upper plateau (Municipality of the Metropolitan District of Quito 2015). This phenomenon may have also been influenced by the location of the new International Airport of Quito (Mariscal Sucre Airport), inaugurated in 2012 and located in Tababela, one of the rural parishes of the MDQ in the eastern valleys. This new urban expansion zone is in permanent transformation and, depending on the ecological and socioeconomic conditions, this expansion can present diverse characteristics.

## Definition of transects and study samples

Based on the previous study of Ortiz-Báez et al. (2021) and in order to cover the extension and diversity of the MDQ periurban expansion in a very detailed scale, six transects were defined. These transects started from two urban centralities[1] and they move towards the eastern rural parishes in 10°, 45° and 90° angles, covering the whole expansion area from the north to the south, allowing us to have a wide perspective of the complexity of the MDQ urban-rural gradient but avoiding eventual underlying patterns (Figure 3). Within the transects, a total of 64 sample polygons of 1 square

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[1] MDQ has two main urban centralities: one is the old "historical centre" where central and local government offices are located (locations related to political-administrative activities); the second centrality is the "modern centre" (central business district) where the most important economic activities (public and private) are located.

kilometre each (Wadduwage et al. 2017) were defined in order to identify Land Use-Land Covers (LULC) in a very high resolution (1 pixel = 1 m²) through the visual identification of satellite images (ESRI World Imagery) and confirmed by field visits (Figure 4a). The identified LULC classes were: Built-up (all artificial constructions including detached houses, high-rise buildings, or sheds); Road infrastructure (including mega road infrastructure like highways and expressways and local roads); Tree and Shrub Vegetation, Agriculture (all recognizable plots with agricultural land production); and Bare Soil and Grassland (Figure 4b). Satellite images from two years, 2010 and 2017, were analysed and systemised in order to evaluate the spatiotemporal transformations (Figure 5).

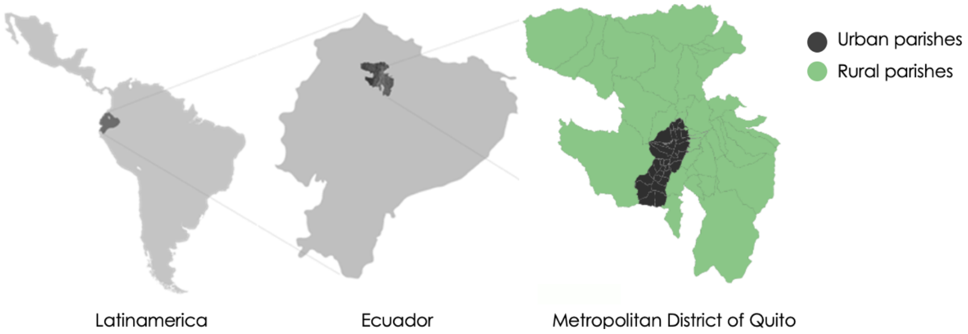

*Figure 1. MDQ location. Source: Gobierno Abierto (2021)*

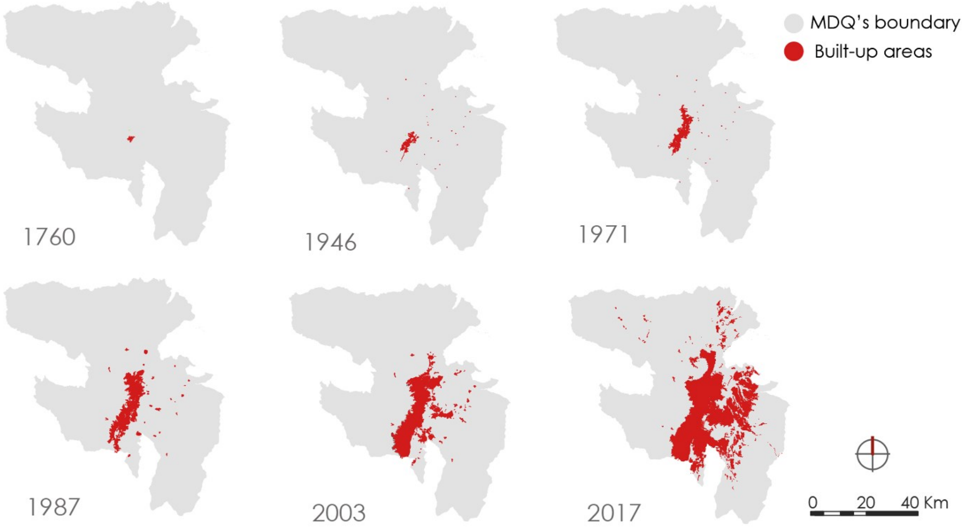

*Figure 2. MDQ location and evolution of built-up areas from 1760 to 2017. Source: Municipality of the Metropolitan District of Quito (2021)*

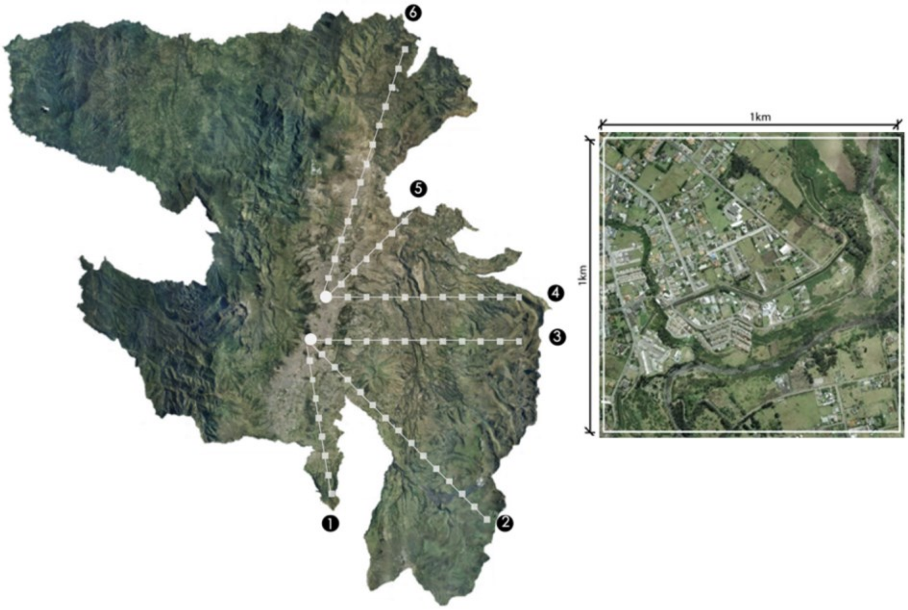

*Figure 3. Transects and samples definition (the location of the 6 transects and the 64 samples; the dimension and scale of one of the samples)*

*Figure 4. Satellite interpretation process and the construction of raster images with Land Use Land Covers*

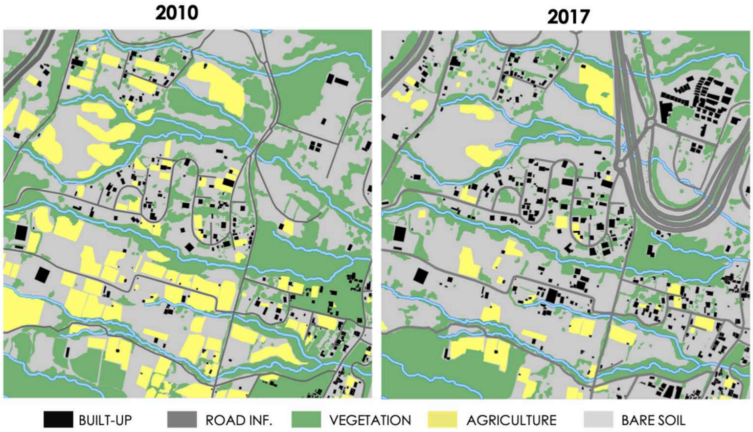

*Figure 5. Sample of raster images and LULC identification for the years 2010 and 2017*

## Landscape metrics calculation

Since there is a strong effect of patterns over processes (Bogaert et al. 2015), the landscape metrics have shown to be a strategic tool to quantify specific spatial patterns such as area, density, dominance, diversity, and isolation, among others (Shrestha et al. 2012, Liu and Weng 2013, Kumar et al. 2018). In order to prove our spatiotemporal hypotheses, five metrics were calculated using the software FRAGSTATS 4.2.1: (1) Percentage of Landscape (PLAND); (2) Patch Density (PD); (3) Average Area (A_MN); (4) Larger Patch Index (LPI) which represents the area of the largest patch and it is an indicator of spatial dominance; and (5) Euclidean Nearest-Neighbour Distance (ENN_MN) which calculates the average distance between two patches, showing the levels of isolation (Table 1).

*Table 1. Landscape metrics and their calculation formula*

| Name | Description | Calculation Formula | Notes |
|---|---|---|---|
| Percentage of Landscape (PLAND) | PLAND equals the sum of the areas (m$^2$) of all patches of the corresponding patch type, divided by the total landscape area (m$^2$), multiplied by 100 (to convert to a percentage) | $PLAND = P_i = \frac{\sum_{j=1}^{n} \quad a_{ij}}{A} (100)$ | $P_i$ = proportion of the landscape occupied by patch type (class) i.<br>$a_{ij}$ = area (m$^2$) of patch ij.<br>A = total landscape area (m$^2$). |
| Patch Density (PD) | PD equals the number of patches of the corresponding patch type divided by the total landscape area (m$^2$), multiplied by 10,000 and 100 (to convert to 100 hectares) | $PD = \frac{n_i}{A} (10.000)(100)$ | $n_i$ = number of patches in the landscape of patch type (class) i.<br>A = total landscape area (m$^2$). |

| Name | Description | Calculation Formula | Notes |
|---|---|---|---|
| Average Area (A_MN) | A_MN equals the sum of the areas (m²) of all patches of the corresponding patch type, divided by the number of patches of the same type, divided by 10,000 (to covert to hectares) | $A\_MN = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}\left(\frac{1}{10.000}\right)$ | $a_{ij}$ = area (m²) of patch ij.<br>$n_i$ = number of patches in the landscape of patch type (class) i. |
| Larger Patch Index (LPI) | LPI equals the area (m²) of the largest patch of the corresponding patch type divided by the total landscape area (m²), multiplied by 100 (to convert to a percentage) | $LPI = \frac{(a_{ij})}{A}(100)$ | $a_{ij}$ = area (m²) of patch ij.<br>A = total landscape area (m²). |
| Euclidean Nearest-Neighbour Distance (ENN_MN) | ENN equals the sum of the distance (m) to the nearest neighbouring patch of the same type, based on the shortest cell centre-cell centre distance, divided by the number of patches of the same type. | $ENN\_MN = \frac{\sum_{j=1}^{n} h_{ij}}{n'_i}$ | $h_{ij}$ = distance (m) from patch ij to nearest neighbouring patch of the same type (class), based on patch edge-to-edge distance, computed from cell centre to cell centre. |

## Assessment of landscape metrics

First, a Wilcoxon Rank-Sum test was performed to evaluate the differences of landscape metrics between the two years of study, for each one of the LULC categories. This test is also known as the Mann Whitney Wilcoxon test, and it is a non-parametric statistic applied to evaluate whether two paired samples are statistically different. In the present research, we are evaluating the differences in landscape metrics between 2010 and 2017 of the same LULC class (e.g., Built-up). In this sense, we are analysing two paired samples: the same LULC class for 2010 and 2017. The null hypothesis of the test is having differences between the pair members equal to zero. Additionally, we calculated the Kruskal-Wallis test to assess if landscape metrics differences exist along the transects as we move away from the city centre. This test is also known as One Factor ANOVA of Kruskal-Wallis for k samples. The test variables were the landscape metrics, and the grouping variable was the kilometrage categories (nominal variable). Thus, with this test we evaluated whether statistically significant differences of landscape metrics values exist between the different kilometrages for all the transects of the study area. The null hypothesis of the Kruskal-Wallis test is having the same distribution of the landscape metrics values between all kilometrage categories. This analysis was separately applied for the two years of the study. Finally, in order to have a more specific outlook of the pattern's transformation in each transect and sample independently, an analysis of the normalised metrics variation (percentage of change comparing the two years) was developed.

### Land change transition probability

The Markov chain modelling technique was applied, as a method to forecast the tendency of LULC's transformation in the MDQ urban-rural gradient. This tool has shown to be one of the most effective in quantitative simulations and it has been widely applied in land use change evolution studies (Guan et al. 2011, Mansour et al. 2020, Da Cunha et al. 2021, Rahnama 2021, Wang et al. 2021). This technique is a stochastic model based on computing a probability matrix of transition and it randomly simulates the changing covers, calculating the rates of all possible transitions between various land covers. The Markov chain's analysis describes land cover changes from one period to another and it predicts future tendencies of change (Mansour et al. 2020, Cunha et al. 2021, Rahnama 2021). Using the software Idrisi 17.0, a Markovian transition estimation was developed for the year 2024.

## Results

For the general LULC transformation between 2010 and 2017 (Table 2), the Vegetation cover shows the greatest reduction in this time period, with -2.23%, followed by Bare-soil and Agriculture covers with -1.57% and -1.29 respectively. In contrast, the covers show an increase are Built-up and Roads, confirming that this study area is undergoing transformations due to urban expansion. The Built-up cover shows the highest net percentage of increment, with 12.43%, followed by Road infrastructure with 9.09%.

*Table 2. LULC general changes between 2010 and 2017*

| | **2010** | | **2017** | | **2010-2017 Changes** |
|---|---|---|---|---|---|
| | **Area (Ha)** | **% of total area** | **Area (Ha)** | **% of total area** | **% of change** |
| Built-up | 515.7 | 8.1 | 579.8 | 9.1 | 12.43 |
| Road | 374.9 | 5.9 | 409.0 | 6.4 | 9.09 |
| Vegetation | 1392.0 | 21.7 | 1360.9 | 21.3 | -2.23 |
| Agriculture | 571.9 | 8.9 | 564.5 | 8.8 | -1.29 |
| Bare-soil | 3459.8 | 54.1 | 3405.5 | 53.2 | -1.57 |

### Differences of landscape metrics between the two years

When comparing the differences of metrics between years, interesting outcomes were obtained. Regarding the land cover of built-up, the results are striking – significant differences or changes were identified for all the metrics, with 99% of confidence for

PLAND, PD, LPI and A_MN, and 95% of confidence for ENN_MN, showing that the quantity and spatial structure of built-up land use has had an important dynamic and it changed through the time. These results also suggest an advance of urban frontier between the two years considered. Furthermore, in the case of the category of roads, significant changes were identified for the metrics PLAND and LPI. In the case of the agricultural cover, there is a statistically significant difference (90% of confidence) of the metric percentage of landscape (PLAND) between 2000 and 2017 (Table 3).

*Table 3. Wilcoxon test comparing the metrics between 2010 and 2017 for each land use-land cover considered*

| | PLAND | PD | LPI | A_MN | ENN_MN |
|---|---|---|---|---|---|
| Built-up | 0.000*** | 0.005*** | 0.001*** | 0.000*** | 0.029** |
| Roads | 0.006*** | 0.928 | 0.016** | 0.929 | 0.995 |
| Vegetation | 0.646 | 0.531 | 0.760 | 0.695 | 0.335 |
| Agriculture | 0.080* | 0.464 | 0.347 | 0.343 | 0.791 |
| Bare-soil | 0.206 | 0.414 | 0.127 | 0.792 | 0.321 |

## Differences on landscape metrics along the transects

For the two years of study, statistically significant differences (95% and 99% of confidence) in all the landscape metrics along transects were identified for the LULC classes of Built-up and Roads Results (Table 4). For the metric LPI, Vegetation and Agriculture did not change for the year 2010, while for the year 2017 these LULC classes experienced significant differences (95% of confidence) along the transects. PD in Agriculture did not change in 2010, while it significantly changed (99% of confidence) in the year 2017, showing greater dynamics in this last period. In 2010, Bare-Soil only changed along transects in PD and LPI, and in 2017, only changed in PD along transects.

*Table 4. Kruskal-Wallis test results to assessing the differences of landscape metrics along the transects (distance to the centre), for 2010 and 2017*

| | | PLAND | PD | LPI | A_MN | ENN_MN |
|---|---|---|---|---|---|---|
| **2010** | **Built-up** | 0.000*** | 0.006*** | 0.005*** | 0.006*** | 0.000*** |
| | **Roads** | 0.000*** | 0.018** | 0.001*** | 0.048** | 0.008*** |
| | **Vegetation** | 0.036** | 0.027** | 0.051 | 0.005*** | 0.245 |
| | **Agriculture** | 0.046** | 0.061 | 0.080 | 0.023** | 0.099 |
| | **Bare-Soil** | 0.722 | 0.007*** | 0.031** | 0.084 | 0.063 |
| **2007** | **Built-up** | 0.000*** | 0.006*** | 0.020** | 0.013** | 0.000*** |
| | **Roads** | 0.000*** | 0.006*** | 0.000*** | 0.036** | 0.006*** |
| | **Vegetation** | 0.040** | 0.008*** | 0.024** | 0.004*** | 0.281 |
| | **Agriculture** | 0.005*** | 0.010*** | 0.019** | 0.014** | 0.056 |
| | **Bare-Soil** | 0.673 | 0.003*** | 0.105 | 0.053 | 0.097 |

## Analysis of landscape structure temporal variation along the transects

While observing the percentage of change between the two years along each gradient, some relevant and more specific features were found. For the Agriculture cover, when comparing the PLAND variation between the two years, this land cover tends to be reduced in most samples, especially in those closest to the urban centre (Figure 6). However, there are some peaks where an increase in the percentage of agricultural land is observed; these coincide with the sectors with strong agricultural potential such as Puéllaro, Pifo or Cotogchoa. On the other hand, the agriculture cover tends to reduce its AREA_MN and LPI in almost all samples, regardless of their distance to the urban centre. This shows a tendency of plots fragmentation as a result of land use changing from rural to urban (where lots can be smaller).

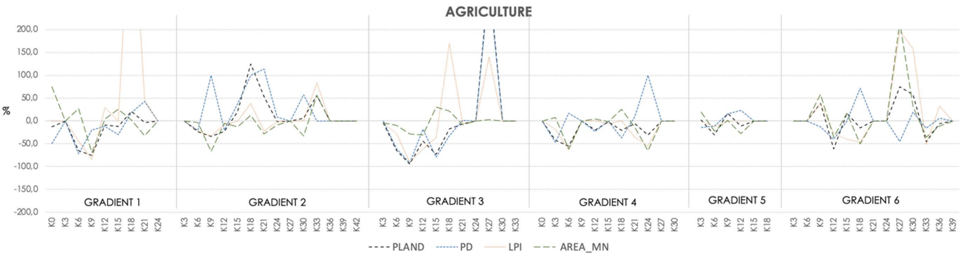

*Figure 6. Metrics percentage of change for Agriculture cover along gradients.*
*Note: for the following graphics, K refers to Kilometres away from the urban centre*

When observing the Vegetation cover and the metrics temporal variation, processes of fragmentation can be identified in various sites. This can be deduced, on the one hand, for the reduction of the patches mean area (A_MN) and the larger patch index (LPI), and on the other hand, due to the increase of the number of patches (PD) at the same spot (Figure 7). This is particularly evident in the Kilometre 24 in gradient 2 (Conocoto) and at the beginning of gradients 3 (Cumbayá), 4 (Nayón) and 5 (Pomasqui). If we compare all these samples with the PLAND of the Built-up cover (Figure 8), we can confirm that all these sectors present a high building increment in the analysed period of time.

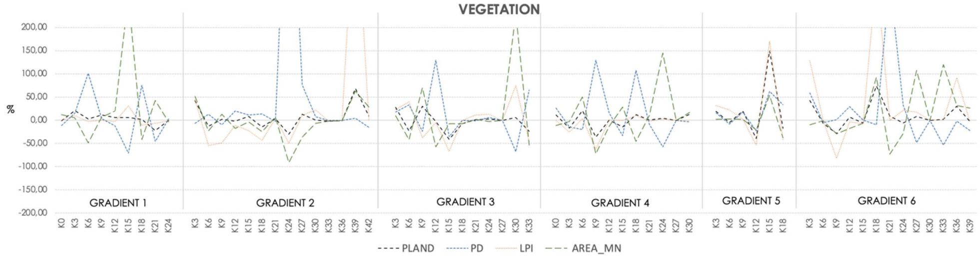

*Figure 7. Metrics percentage of change for Vegetation cover along gradients*

When analysing the temporal variation of PLAND for the Built-up cover, we can see that there is an overall tendency to increase buildings in all gradients, although at different levels of intensity and distances from the urban centre. The highest intensity of built-up growth tends to match the location of traditional rural settlements (cabeceras parroquiales) situated in the periurban area. On the other hand, when analysing the temporal variation for the ENN_MN for the Built-up cover, in most samples, the distances tend to be reduced. This shows that there is a general propensity to densification and agglomeration through all the urban-rural gradients in the MDQ.

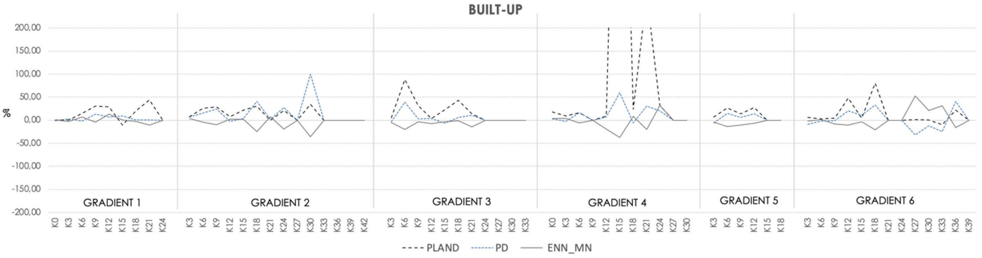

*Figure 8. Metrics percentage of change for Built-up cover along gradients*

Finally, when comparing the Built-up PLAND variation with the Roads PLAND variation (Figure 9), we can observe a tendency of a correspondence with the increment of roads and the increment of buildings in all gradients. In fact, applying the Spearman test , a correlation coefficient of 0.34 and a p value of 0.005 were found, which indicates a 34% strength of association between the two variables; this association is positive (directly proportional) and highly significant (99% confidence). However, what happens in gradient 5 is striking, since there is a significant increase in buildings but without an important increase in roads. Additionally, it is important to mention that the highest growth point of Built-up (Gradient 3, Kilometre 9) coincides with the intersection of the highway named Ruta Viva, which was built to connect the city of Quito with the new international airport.

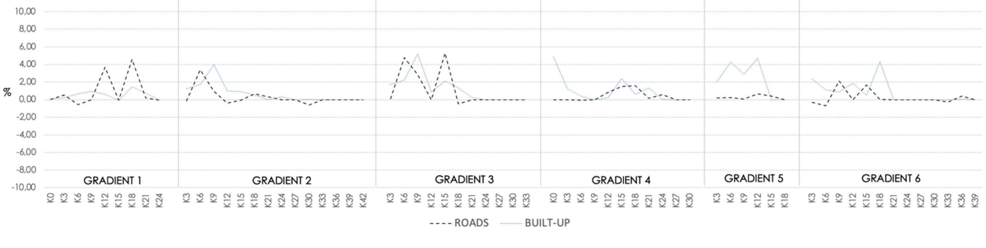

*Figure 9. Comparison of temporal variation of PLAND between Roads and Built-up covers*

## Land change transition probability matrix

In the Markov transition probability matrix (Table 5), the higher values can be identified on the diagonal, which means that the highest probability is that coverage will remain stable in the same class until 2024. Regarding the probabilities of change, based on the previous transformations of 2010-2017, there is a probability of 0.02 that the vegetation covers will become roads and a probability of 0.15 of becoming bare-soil. There is also a probability of 0.21 that agriculture covers will become bare-soil. Finally, the probability of bare-soil becoming vegetation is 0.08, in built-up is 0.03 and in agriculture is 0.06.

*Table 5. Transition probability matrix between 2010 and 2017 for predicting the LULC transformation in 2024*

| | Vegetation | Built-up | Roads | Agriculture | Bare-soil |
|---|---|---|---|---|---|
| Vegetation | **0.8094** | 0.0078 | 0.0201 | 0.0038 | 0.1565 |
| Built-up | 0.0012 | **0.9628** | 0.0049 | 0.0004 | 0.0030 |
| Roads | 0.0043 | 0.0035 | **0.9550** | 0.0007 | 0.0035 |
| Agriculture | 0.0174 | 0.0137 | 0.0048 | **0.7251** | 0.2178 |
| Bare-soil | 0.0819 | 0.0318 | 0.0138 | 0.0552 | **0.8162** |

# Discussion

In a previous research, current landscape patterns in the MDQ urban-rural gradient have been addressed (Ortiz-Báez et al. 2021). However, analysing the spatiotemporal dynamics in the last years has allowed us to have a more precise understanding of the transformation trends that will determine the territorial development in the coming years. The analysis of the temporal variation in various landscape metrics, enables a richer visualisation of the landscape composition and configuration, and their transformation tendency. Additionally, the use of transects and the detailed scale of the samples allowed us to make a very meticulous and detailed assessment of the landscape features along transects, without losing the general perspective of the MDQ, which facilitates the analyses of territorial diversity within the urban-rural gradient.

Land use change in the MDQ is a key topic, since its demographic development has evolved significantly since the decade of 1970 and with greater intensity in recent years, but particularly because its physical urban tissue has shown to be expanding in an accelerated and intensive way. There are important socioecological implications in this expansion tendency. On the one hand, there are several impacts on the natural and agricultural areas that are not always perceptible but they are threatening the territorial environmental sustainability. And, on the other hand, new urban peripheral settlements are producing socioeconomic problems such as the proliferation of low density gated communities or the concentration of poverty settlements in peripheral areas (Sabatini et al. 2001, Sabatini 2003, Municipality of the Metropolitan District of Quito 2014, Serrano and Durán 2020, Herrero Olarte 2021).

Our results provide clear evidence of significant changes in the Built-up cover, in all landscape metrics between the two years of study, which confirms the urban expansion of the city of Quito towards the eastern valleys of the MDQ. In these valleys, there are some parishes that administratively are considered rural (e.g., Cumbayá, Tumbaco, Conocoto), but that have become practically urban in structure and in function. These territories, that were previously considered distant and inaccessible, have become the new areas of dispersed urbanisation. However, this process of urban expansion is not linear, it presents various peaks which can be observed in the PLAND variation. These peaks are directly associated with the presence of traditional rural settlements (cabeceras parroquiales) which were once in the outskirts of the city, but now they are facing micro extension/conurbation processes (Ortiz-Báez et al. 2021). Since these settlements are geographically separated, we can confirm a fragmented urbanisation pattern in the MDQ periurban areas.

Furthermore, the significant change of Roads´ PLAND between 2010 and 2017 is also indicative of the landscape functionality driven urban expansion: the development of roads that connect the city of Quito with the eastern rural parishes. In this way, the statistical analyses of the transects suggested the high variation of landscape metrics for the Built-up and Roads LULC classes, which provides important evidence of the landscape dynamics involving the rural transformation to urban. Also, the analysis of the Euclidean Nearest Neighbour (ENN_MN) metric 2010-2017 variation evidences a tendency towards building densification along all gradients. Various authors have affirmed that the new road infrastructure tends to accelerate the urban expansion (Aguilar 2002, Borsdorf 2003, Serrano and Durán 2020). This hypothesis can be confirmed in the MDQ case since the Roads and Built-up PLAND increases in parallel. Also, the higher Built-up increment occurs in the samples crossed by the new highways that connect the central city with the new International Airport of Quito, opened in 2012. At this point, it is worth asking if the municipal planning of these mega road-infrastructures foresaw the impact that they would have on urban expansion. Along with the impact of new road infrastructure on urban expansion, the diffuse pattern, and the lack of efficient public transport in periurban areas, increases the dependency on private motorization. In fact, in the MDQ, the private automotive fleet has increase in 7% in the last years (Municipality of the Metropolitan District of Quito 2021) and the daily commuting from the rural valleys of Cumbayá, Tumbaco and Los Chillos to the city centre has increased from 40 000 in 2008 to 140 000 in 2019 (Municipality of the Metropolitan District of Quito 2009, La Hora 2019). This not only affects traffic congestion and travel times, but it has important environmental effects: in the MDQ, 56% of the carbon footprint is caused by the emissions from transport vehicle emissions (Municipality of the Metropolitan District of Quito 2015).

Despite the fact that the new road infrastructure has demonstrated to be a main driver of urban expansion as mentioned above, this study presents a particular case that deserves to be discussed from a socioeconomic perspective. Gradient 5, which corresponds to the rural parish of Calderón, shows one of the most pronounced increases in buildings in the period 2010-2017. However, this parish does not have a direct influence of new road infrastructure during that period of time. In this case, the noticeable urban intensification would be associated with other drivers. Informal building growth has been one of the main challenges of urban expansion in the MDQ. Speculation and high land prices in central parishes have led to the informal and deregulated occupation of nearby rural parishes (Guerreo Miranda 2011). This is the case of Calderón, where until 2010, 90% of its settlements were illegal (Municipality of the Metropolitan District of Quito 2011). Evidence has shown that irregular growth processes lack infrastructure, facilities, economic opportunities and basic services which affect the price of the land (Cabrera and Plaza 2016, Weku et al. 2019). Currently, Calderón has one of the lowest land prices on the market, which makes it an attractive place for the migration of low socioeconomic classes. On another hand, facing the high density of the parish, the local government has made efforts to provide new urban services and facilities such as the 2015 inaugurated Calderón Hospital, among others, making the parish more attractive for new migrants.

Furthermore, in the studied period of time, private agents have also seen an opportunity to promote real estate projects focused on middle and low economies, which are focused in guaranteeing housing but not always in an adequate urban context. Thus, the mix of these factors: irregular growth, low land prices, new social services, and speculation in the real estate market with a focus on the middle and lower classes, appear to be accelerators of urban expansion in the parish of Calderón. This development pattern seems to be recurrent in Latin-American realities. According to Frediani (2009), the diffuse city in Latin-America presents enclaves of poverty in its peripheries, which also present accelerated rates of expansion. This is consistent with the study of Herrero Olarte (2021) for the city of Quito, where it is stated that there is a direct relationship between multidimensional poverty and the distance to the city centrality.

Regarding the environmental implications in the 2010-2017 period, Agriculture and Vegetation covers significantly varied along the transects, suggesting the modification of ecological systems during the last years. This statistical evidence corresponds with other transformations in the territory, such as the alterations of rural livelihoods due to development of new highways connecting the city to the Airport. Regarding the Agriculture cover, the analysis confirms that it has been reduced in the last decade and, according to the Markov's probability matrix, it tends to be reduced even more in the following years. This is particularly critical, since the area where the urban tissue is expanding, is also the area with more concentration of soil with agricultural vocation in the MDQ (Municipality of Quito 2016). Another relevant finding is the reduction of the Patch Mean Area (A_MN) and the Larger Patch Index (LPI), revealing a tendency of plot fragmentation which can be a result of the land use change from rural to urban.

Indeed, despite the metropolitan land use regulation, in which rural land use has particular restrictions in order to protect it (such as a minimum lot size), there are several regulatory and legal gaps that continue allowing the division of lots. One of them is the legal tool of "acciones y derechos" (shares and rights) in which a percentage of the property can be sold without legally changing the plot size, but this allows the new owner to change the use within its percentage of land. Another frequently used legal mechanism, especially by real estate companies, is the "horizontal property", where a dwelling unit is sold as a percentage share within a large lot. The latter is the most common method to implement gated communities and it has started to be used more frequently (Quito Metropolitan Institute of Urban Planning 2018). In this scenario, agricultural practices may tend to weaken even further, considering that by 2014 only 5% of the population living in rural parishes was engaged in agricultural production which has a socioeconomic impact (Municipality of Quito 2016).

Finally, regarding the Vegetation cover, after analysing the 2010-2017 metrics variation, processes of fragmentation were identified in various sites. This can be inferred due to the reduction of the Patch Mean Area (A_MN) and the Larger Patch Index (LPI), while there is an increment of Number of Patches (PD). Fragmentation is one of the major environmental concerns, due to its effects on the ecological functions and processes which can result in the damage of natural habitats, the reduction of ecosystem services and consequently of basic human needs (Shrestha et al. 2012, Kumar et al. 2018). The sites that present the most evident processes of fragmentation match areas with higher increase in Built-up covers. Observing the Built-up ENN_Mean metric, we can also relate these areas with "medium to low" density patterns of built expansion, related for example with the accelerated suburban sprawl in the parishes of Cumbayá, Nayón and Conocoto. According to Shrestha et al. (2012), the low-density developments contribute to increasing the level of land fragmentation and they typically happen on the urban-rural fringe.

# Conclusions

The MDQ is undergoing a process of intensive urban expansion towards its eastern valleys. However, the level and patterns of transformation are different between the gradients and along the gradients, showing the diversity within this periurban territory. The calculation of landscape metrics has proven to be an effective tool to assess the spatial patterns of these territorial transformations and to identify such diversity, and it can be a key tool to formulate and implement land use planning policies with an environmental and socioeconomic perspective.

There are important socioecological implications in this expansion pattern. The implementation of new road infrastructure appears to be one of the major factors accelerating urbanisation, since there is a correspondence between the increase of roads and buildings in the studied time period. This is particularly evident with the Ruta Viva highway, built to connect the new airport of Quito and where one of the highest levels of increase in buildings were found. However, as a result of the diversity of patterns and processes in the periurban area of the MDQ, the particular case of the parish of Calderón stands out, where (unlike the rest of the study areas) there has been a significant increase in buildings without a corresponding increase in roads. Other socioeconomic drivers, such as informal settlements, low land price, new public investment and low class-focused real estate speculation seems to explain the accelerated urban growth of this rural parish. The variety of dynamics within the MDQ evidence the complexity of the urbanisation phenomenon, where specific plans should be part of the agenda. Calderón's urban development model is a recurrent pattern in Latin-American diffuse cities, where enclaves of poverty in the peripheries are growing rapidly.

Finally, our analysis demonstrates the vulnerability of the natural and agricultural ecosystems in the MDQ. The tendency of Agriculture PLAND, A_MN and LPI reduction, as well as the increment of fragmentation processes in the Vegetation cover, show the fragility of territorial environmental sustainability. The results of this study can be a key input for the formulation of more specific policies for the conservation and recovery of ecosystems affected by these accelerated and little-known processes of urban expansion.

Research on the landscape dynamics is particularly important for sustainable development and the results for the MDQ could give key information for the formulation of development policies and planning strategies in the long term. Furthermore, the analysis of changes of MDQ urban-rural landscapes, can contribute to a better understanding of the urban expansion of Latin American metropolitan areas, considering that Latin America is a continent facing a rapid urbanisation process in a context of extreme inequality.

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